ARM Summer Training and Science Applications

Cloud-to-Precipitation Transition Report

Participants:
Andrew Dzambo, University of Oklahoma
Andrew Lesage, University of Utah
Jinjing Tian, University of North Dakota
Mikael Witte, University of California
Haiyang Yu, Stony Brook University

Instructors:
Pavlos Kollias, Stony Brook University
Edward Luke, Brookhaven National Laboratory

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1.0 Cloud-to-Precipitation Transition

Marine stratocumulus clouds exert significant negative radiative forcing due to their large areal extent, high albedo (shortwave forcing), and low cloud top (longwave forcing, e.g., Zelinka et al. 2012), yet the representation of these clouds in global climate models is problematic due to the small spatial scales of relevant physical processes (Hsieh et al. 2009). Along with entrainment, precipitation is one of the primary sinks of moisture and thus serves as a major determinant of the lifetime and morphology of these clouds (Stevens et al. 2005; Mechoso et al. 2014). Early detection of the onset of drizzle has therefore been a longtime goal of the observational community. Past work on this topic has led to diagnostic criteria that range from trivial passive techniques (collecting ground precipitation) to complex, active remote-sensing strategies (e.g., theoretically derived radar reflectivity thresholds as a function of altitude, Liu et al. 2008). Generally, these techniques may detect the presence of mature drizzle but are unable to diagnose the onset of precipitation—i.e., by the time drizzle is detected it is already fully developed. This work instead aims to develop a method to detect the presence of embryonic drizzle drops before precipitation is observed at cloud base.

We used observational data to evaluate techniques for detecting drizzle. Two cases were selected from the ARM Mobile Facility deployment in the Azores, 27 July 2010 and 8 November 2010. We used the W-band ARM Cloud Radar (WACR) and Ceilometer observations from the MicroARSCL data set. Ceilometer first cloud base, radar reflectivity, and various Doppler moments (Doppler velocity power spectrum, spectrum width, and spectrum skewness) were smoothed to 2-, 5-, and 10-minute moving means. Previous studies have proposed using radar reflectivity thresholds as a basis for identifying the presence of drizzle (Chin et al.,2000; Kato et al. 2001; Kogan et al. 2005). For this study, -15 dBZ and -20 dBZ were selected for comparison; a cloud is considered to be "drizzling" if maximum reflectivity exceeded those thresholds at any level. The 27 July case resulted in detection of drizzle 43.1% (-15 dBZ threshold) or 64.4% (-20 dBZ) of the time while the 8 November case detected drizzle 15.9% (-15 dBZ) or 24.0% (-20 dBZ) of the time.

An alternative method for detecting drizzle involved Ceilometer first cloud base height and radar reflectivity. The Ceilometer cloud base is unaffected by light drizzle while the WACR reflectivity is highly sensitive to the presence of any drizzle drops. As a result, the difference between the Ceilometer first cloud base height and the Cloud Radar height are used to indicate drizzle when the difference in cloud base height exceeds 100 m. A threshold of -45 dBZ was used to identify cloud base from the cloud radar data. The unsmoothed data identified drizzle in the 27 July case 53.6% of the time and in the 8 November case 56.4% of the time. The July detection rate is comparable to the reflectivity threshold technique while the November detection rate is much higher, identifying drizzle a significant portion of the time when the maximum reflectivity was only between -20 dBZ and -25 dBZ.

The Doppler velocity power spectrum retrieved by the WACR encodes information about particle size via the monotonically increasing relationship between drop size and drop terminal velocity, although the spectrum does not correspond one to one with the particle size distribution (PSD) due to mean air motion, the spectrum-broadening effects of turbulence, and the strongly nonlinear relationship between drop size and reflected power (Z(v)~D6). Higher-order moments such as the skewness of the Doppler spectrum can be used to identify the onset of drizzle because of the link to the PSD: positive skewness indicates a "tail" of power returned from relatively large drops with small drops dominating the total reflectivity, while negative skewness indicates the converse (large drops dominate the spectrum, tail due to small drops). At each time step, the cloud was subdivided into 10 normalized-height layers from cloud base to cloud top and reflectivity bins of 2 dBZ were used to analyze mean values of Doppler velocity and the skewness of the velocity spectrum as a function of radar reflectivity at each cloud layer. Skewness was found to be a powerful variable for understanding the relative contribution of cloud and drizzle particle-size distributions, as the earliest production of drizzle particles leads to positive skewness. At each level, we chose a value of half the observed maximum skewness as a threshold. To be designated as “drizzling,” a column must have multiple gates meeting the threshold criterion. This differs from the other techniques considered, which either use a single value at cloud base or the maximum value of an entire column as their detection criteria.

In order to evaluate the detection techniques, we developed a forward model to simulate the Doppler radar spectrum, given a particle size distribution and tuned parameters of turbulence and noise level (Kollias et al. 2011). The initial droplet size-distribution profiles were prescribed as a combination of two modes: cloud droplets only and drizzle drops only. These spectra were derived from a single-column, steady-state microphysical model with only condensation/evaporation and collision-coalescence activated (i.e., no Cloud Condensation Nucleii [CNN] activation, sedimentation, breakup, etc.). Three cases with the same liquid water content profile but varying total drop number concentration (50 cm-3, 200 cm-3, and 400 cm-3) were tested to verify the feasibility of the detection techniques. Sensitivity testing using different turbulence broadening and noise levels was performed with 1,000 members for each combination of turbulent spectrum broadening and noise. The standard derivation of each ensemble is interpreted as the model uncertainty.

Results from the two observational cases show that the skewness threshold technique agrees qualitatively with total radar reflectivity. Figure 1 shows the detection of drizzle onset using the skewness threshold for the 2-minute averaged November case. Generally, the detected drizzle events are correlated with strong radar reflectivity (Fig. 1b and 1c). The strong drizzle events just after 12:00 UTC and between 17:00-24:00 UTC are accurately detected (nearly continuous black dots), with a more intermittent pattern of detection otherwise (Fig. 1b). Applying the threshold technique to the smoother time series (5- or 10-minute moving mean) may improve the precision of drizzle onset by reducing noise. The detected events near the cloud top (Fig. 1a) most likely correspond with the initial stages of the collision-coalescence process (i.e., persistent autoconversion), which implies that the positive skewness of the Doppler spectrum may be considered a fingerprint of the evolution of the particle size distribution.

Using the forward model, we demonstrated that the empirically derived skewness threshold techniques work well in the simulated parameter space. As shown in Figure 2, the skewness of the simulated Doppler spectra increases immediately below cloud top, dominated by the collisional growth of cloud droplets. After the skewness reaches a maximum value, drizzle drops form and the total skewness moves to negative values. As drizzle begins to dominate the shape of the Doppler spectrum, minimum skewness is reached. The thresholds derived from the two observational cases works well overall, as the intersection of simulated skewness profiles and thresholds are close to cloud top where drizzle is initiated. However, the sensitivity tests with a strong turbulence broadening effect show that there is no intersection between the simulated skewness and the thresholds (Fig. 2f), indicating that using skewness only may not be sufficient to detect drizzle onset in all cases. Better detection may be obtained by combining other parameters (e.g., radar reflectivity, mean Doppler velocity, or spectrum width) derived from the Doppler spectrum with the skewness threshold. Furthermore, the ratio of drizzle mass to cloud droplet mass in Figure 2(g-i) shows that less drizzle is formed when the total number concentration is increased, since more drops are competing for the same amount of liquid water. As the mean drop size decreases, drop collision rates also decrease, pushing the formation of drizzle to lower levels in the cloud.

As demonstrated by observation and a forward radar simulator, the skewness of the Doppler radar spectrum performs as well or better as a detector of drizzle onset than traditional radar reflectivity thresholds. Mathematically, skewness exhibits heightened sensitivity to large droplets (drizzle) because it is a high-order moment of the Doppler spectrum and thus identifies the onset of drizzle much earlier than radar reflectivity, the zeroth moment of the Doppler spectrum. Skewness detects the shape transition of the Doppler spectrum, which can be thought of as a measure of the evolution of the particle size distribution. The observational case studies indicate it detects both collision-coalescence and drizzle onset, so skewness also serves as a "fingerprint" of certain microphysical processes. Combination with other parameters such as radar reflectivity, mean Doppler velocity, and spectrum width are expected to better detect drizzle onset. Larger-scale tests based on long-term observations are also necessary to evaluate the feasibility and sensitivity of the skewness threshold technique under varying conditions.

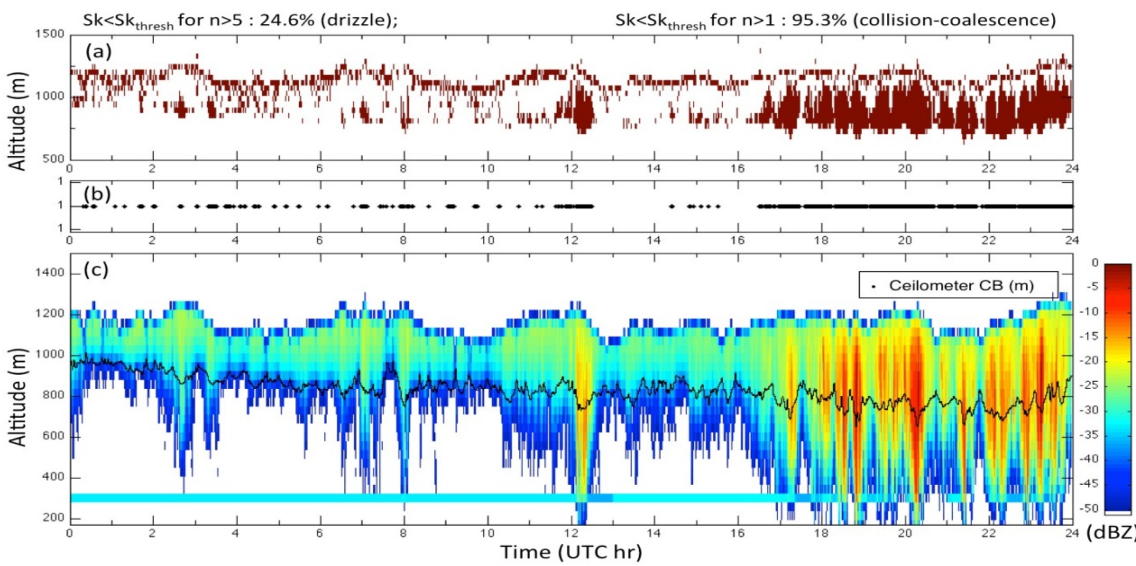

Figure 1. Detection of drizzle onset based on one-day (8 November 2010) of observed Doppler radar spectra from the ARM Mobile Facility deployment on Graciosa Island, Azores, smoothed to 2-minute moving average. a) Pixels depict regions where the skewness (Sk) of the Doppler Radar spectrum is lower than the threshold (Skthresh, see Figure 2 for threshold derivation). b) Drizzle events (defined as 5 or more pixels in a column meeting the threshold criterion) are masked as black dots. c) Observed total Doppler Radar reflectivity (shaded, units: dBZ) by W-band ARM Cloud Radar (WACR) and first (lowest) cloud base height (black solid line, units: m) detected by the ceilometer.

2.0 References

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